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Uplift of the western border of the Altiplano on a west-vergent thrust system, Northern Chile

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Abstract — A high angle, west-vergent thrust system (WTS) located along the western border of the Altiplano in Northern Chile caused the westward translation of the metamorphic pre-Cambrian basement and Mesozoic rocks over late Tertiary deposits. This WTS, which was essential to the build-up of the western Altiplano, developed principally between 15 and 4.8 Ma. The chronological sequence of faults indicate a back-thrusting. The WTS forms an overstep thrust sequence with vertical throws increasing from West to East and exposes in this direction increasingly older units over younger ones.

Taking the paleolake deposits of the Chucal Formation (25–19 Ma) and the ignimbrites of Oxaya Formation (19 Ma) as two regional reference levels, it is possible to calculate a 4,000 ± 200 m uplift associated to the WTS and a 392 ± 20 m/Ma uplift rate.

The WTS on the west side of de Altiplano and the east vergent thrust and fold belt on the east border, indicate that this plateau is essentially a compressive asymmetric structure, formed by two thrust "belts" with opposing vergencies.

Resumen — El borde occidental del Altiplano está formado por un sistema fallado y plegado de alto ángulo con vergencia hacia el Oeste (WTS). Este sistema involucra el alzamiento de un basamento metamórfico de edad precámbrica y secuencias sedimentarias del Mesozoico, falladas sobre unidades sedimentarias y volcánicas de edad terciaria media y superior.

El alzamiento principal del Altiplano, en el extremo norte de Chile, se habría desarrollado entre los 15 y 4.8 Ma y habría sido facilitado por este sistema de fallas, cuya edad es menor hacia el antepaís y cuyo desplazamiento vertical aumenta en la misma dirección. Tomando como niveles de referencia regional las ignimbritas de la Formación Oxaya y la paleoelevación a la cual fueron generadas las sedimentitas de la Formación Chucal (lacustre, 25–19 Ma), el alzamiento tectónico asociado al WTS habría sido del orden de los 4.000 ± 200 m con una tasa de 392 ± 20 m/Ma.

La existencia de un sistema fallado de vergencia occidental en el borde oeste del Altiplano indica que esta megaunidad es, esencialmente, una estructura compresiva asimétrica formada por dos sistemas de empuje de vergencias opuestas: el sistema de empuje de las Sierras Subandinas y el WTS, ambos iniciados durante el Oligoceno.

INTRODUCTION

The origin of the near 4,000 m high Altiplano-Puna plateau, located in the Central Andes, represents one of the most interesting mountain building problems in this part of the range. The uplift of mountain ranges can generally be related to crustal shortening processes. To explain in some mountain ranges the presence of great high plateau like the Tibetan, and the Altiplano-Puna, it seems however, necessary to appeal to a combination of processes involving different amounts of horizontal and vertical mass and energy transport. These processes can be classifed into the following categories: structural shortening, magmatic addition and lithospheric thinning (Allmendinger, 1986).

Several attempts have been made to explain the uplift of the Altiplano-Puna plateau. Suarez *et al.* (1983) suggested that the crustal thickening is caused by repeated underthrusting of the continental crust. Similar views were given by Roeder (1988) and Reutter *et al.* (1988). Isacks (1988) favored the idea that the Altiplano is a result of crustal thickening produced by structural shortening and thermal thinning of the lithosphere (see our discussion). Kono *et al.* (1989) proposed, instead, that magma addition and crustal shortening are the mechanisms that simultaneously operated during the uplift of the Altiplano plateau. In their model, addition of magma prevailed in the western half of the Central Andes, while crustal shortening concentrated in its eastern part, that is: the Eastern Cordillera and the Subandean Ranges.

This article describes a high angle, west-vergent thrust system located on the west border of the Chilean Altiplano, between 18° 30' and 20° South latitude, and discusses its significance for the uplift of the Altiplano plateau.

GEOGRAPHIC AND TECTONIC SETTING

The Altiplano is located in the arid and scarcely glaciated central part of the Central Andes (Gansser, 1973) between 15° and 27° S latitude, where it overlies a 30° east-dipping segment of the subducted oceanic slab; it is bounded to the N and S by flat-slab subduction segments (Barazangi and Isacks, 1976; Cahill and Isacks, 1992).

In the central part of the Central Andes, between 15° and 20° S, in South Peru, North Chile and Southwest Bolivia the following morphostructural units are distinguished, from West to East; Arica Basin (AB), Coastal Range (CR), Central Basin or Central Depression (CB), Altiplano plateau (A) with the volcanic zone to its west side or Western Cordillera (WC), Eastern Cordillera (EC) and Subandean Sierras (SS). South of this area, at the latitude of Antofagasta (23°S) other morphostructural units are developed between the Central Basin and the Puna, the southward continuation of the Altiplano. These are, from West to East: The Precordillera (PC) and the Preandean Depression (PD) (Fig. 1).

The Altiplano-Puna is a 3.7–4.2 Km high plateau located between 15° and 27° S. It is 300 Km wide at is wider section and 1.500 Km long. In northernmost Chile the west boundary of the Altiplano-Puna plateau has a NW-SE orientation which is oblique to the north-south oriented chilean Precordillera and Preandean Depression (Fig. 1). On the Altiplano-Puna surface and in the Preandean Depression south of 23° South latitude, extensive depressions are located: Salars or endorheic basins to the South, formed under very dry climatic conditions with thick evaporitic deposits like the Arizaro, Atacama, Uyuni and Coipasa Salars, and enormous lakes to the North, under more humid climatic conditions, like the Poopo and Titicaca lakes (Fig. 1).

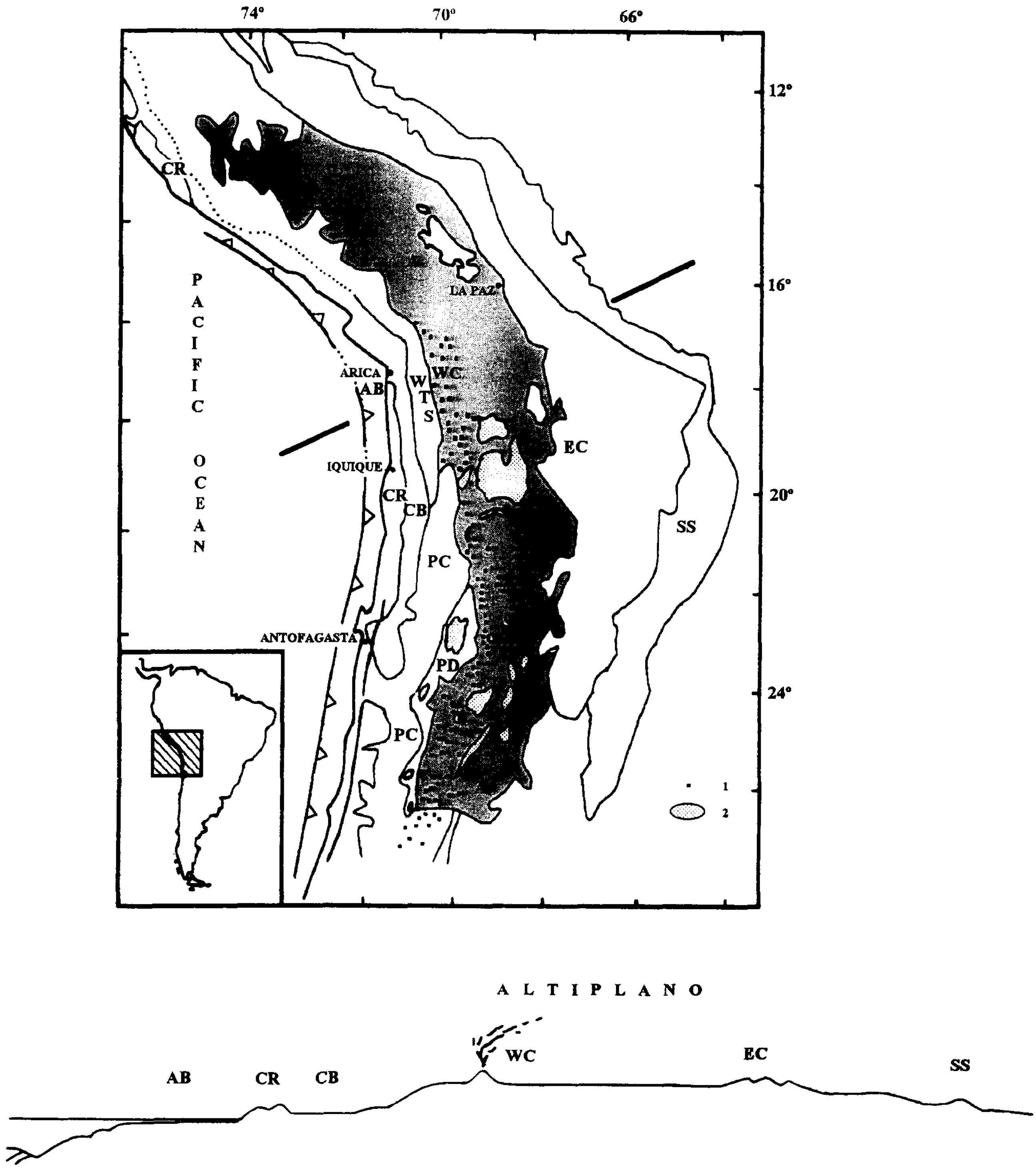

Fig. 1. Location map of the Altiplano in South America and distribution of the morfostructural units of the Central Andes. 1. Volcanic centers, 2 Salars. AB: Arica basin, CR: Coastal Range, CB: Central Basin, WTS: West-vergent Thrust System, PC: Precordillera, PD: Preandean Depression, WC: Western Cordillera, A: Altiplano, EC: Eastern Cordillera, SS: Subandean Sierras.

The Western Cordillera corresponds to the late Cenozoic to Recent volcanic arc. It is nearly 100 Km wide and is formed by scattered late Tertiary to Recent volcanoes built up on the surface of the western Altiplano-Puna Plateau, some of which attain heights over 6,500 meters. The young, mainly active volcanoes are located along the Chile-Bolivia borderline. Between 27° and approximately 23° South latitude the Western Cordillera runs, with a N 10°-15° E orientation, along the middle of the zone of salars. North of 23°S latitude the Western Cordillera has a nearly N 20°W orientation, and cuts obliquely to the salars, which extend, further to the NNE, with no change of orientation. North of 23°S the Western Cordillera is, thus, located to the West of the salar basins. At the latitude of Arica (18° 30'S) the andean structures have an abrupt change in orientation forming the socalled "Bolivian Orocline".

The Subandean Ranges form the easternmost morphostructural unit and correspond to an east-vergent thrust and fold belt with a minimum shortening of 210 Km (Roeder, 1988; Sheffels, 1990; Baby *et al.*, 1992; Schmitz, 1994).

REGIONAL GEOLOGY OF THE WEST BORDER OF THE ALTIPLANO IN NORTHERN CHILE

In the region East of Arica and Iquique and West of the Altiplano, Precambrian, Paleozoic, Mesozoic and Cenozoic rocks are exposed.

The oldest rocks known in this region are the nearly 1.000 Ma low grade "Belén Schists" (Pacci *et al.*, 1980). Schists and gneiss are exposed along a narrow strip on the western edge of the Altiplano plateau between Chapiquiña and Tignamar villages. These rocks are in fault contact with Mesozoic and Cenozoic rocks. This unit has been considered part of the Arequipa Massif (Mpodozis and Ramos, 1989).

Next to the Central Basin, thick siliciclastic and carbonatic marine sequences of Sinemurian-earliest Neocomian age are exposed. At Santuario de las Peñas, a locality 60 km to the East of Arica, these deposits overlie ryolithic tuffs and flows of possible late Triassic age. At Aroma valley, east of Iquique, they uncoformably cover late Paleozoic metasedimentary rocks. These rocks were deposited in the Tarapacá backarc basin (Muñoz *et al.*, 1988; Harambour, 1990; Muñoz and Charrier, 1993; Charrier and Muñoz, in press).

East of Iquique, late Cretaceous ignimbrites and tuffs unconformably cover the east vergently folded marine Jurassic series (Harambour, 1990).

On the west slope of the Altiplano, the marine Mesozoic series are unconformably covered by extensive 600–800 m thick Miocene ignimbritic flows. In the northern Chilean Altiplano these deposits (Oxaya Formation, Salas *et al.*, 1966) have a North-South distribution of more than 150 Km and a total areal extension of near 25.000 Km2. Isotopic determinations on samples of this unit gave ages between 23 and 17 Ma (Lahsen 1982). Age determinations in the study region gave at three localities ages of 19 Ma (see Table 1). At 20° South latitude an equivalent of this unit, the Altos de Pica Formation, gave ages between 17 and 15 Ma (Galli, 1957, 1968; Galli and Dingman, 1962; Baker and Francis, 1978; Lahsen, 1982).

Tertiary deposits exposed along the west margin of the Altiplano and on the western Chilean Altiplano correspond in general to Oligocene to Recent volcanic and

Table 1.

RADIOISOTOIC AGES OF ROCKS OF THE CHILEAN ALTIPLANO BETWEEN 18° 30' SOUTH LATITUDE

N°	Sample N°	Unit	Locality	Rock type	Method	Age (Ma)	Author
1	AJA-177	Lava	Ajoya	Dacite	K-Ar Rt	7.1 ± 0.2 Ma	Worner et. al. (88)
2	NMG-409	Oxaya Fm.	Cerro Tallacollo	Ignimbrite	K-Ar Rt	19.9 ± 1.1 Ma	Fondecyt
3	NMG-412	Oxaya Fm.	Guallatiri	Ignimbrite	K-Ar Rt	19.6 ± 0.7 Ma	Fondecyt
4	NMG-434,2	Intrusive	Quebrada Lluta	Diorite	K-Ar Bi	64.4 ± 2.0 Ma	Fondecyt
5	NMG-461	Ignimbrite	Lago Chungará	Ash-flow tuff	K-Ar Rt	25.4 ± 0.7 Ma	Fondecyt
6	NMG-462,1	Lauca Fm.	Río Lauca	Tuff	K-Ar Rt	2.3 ± 0.7 Ma	ENAP
7	NMG-500	Tarapaca Ignimbrite	Qda. Latagualla	Ignimbrite	K-Ar Rt	16.3 ± 0.7 Ma	Muñoz & Sepulveda (1992)
8	NMG-502	Camiña Ignimbrite	Camiña	Ignimbrite	K-Ar Rt	8.2 ± 0.5 Ma	ENAP
9	NP-33	Oxaya Fm.	Pampa Oxaya	Ignimbrite	K-Ar Bi	19.3 ± 0.8 Ma	Naranjo & Paskof (1985)
10	NP-41	Waillas Ignimbrite	Quebrada Oxa	Ignimbrite	K-Ar Bi	4.4 ± 0.3 Ma	Naranjo & Paskof (1985)
11	NP-47	Waillas Ignimbrite	Chapiquiña	Ignimbrite	K-Ar Bi	4.8 ± 0.3 Ma	Naranjo & Paskof (1985)
12	LAU-102	Lava	Lauca	Andesite	K-AR Rt	10.5 ± 0.3 Ma	Worner et. al (1988)
13	SPR	Esq. de Belen Fm.	Belén	Gneiss	Rb-Sr Rt	> 1000	Pacci et. al. (1980)

Bi: Biotite
Rt: Total rock
ENAP: Empresa Nacional del Petróleo

sedimentary rocks. These units correspond to 25 million years old ingnimbrites and thick Oligocene-early Miocene fluvio-lacustrine (1,000 m thick Chucal and Putani Fms., on the Altiplano) and middle Miocene volcano-detritic (Lupica Fm., 750 m thick on the west margin) (Muñoz, 1991). The ignimbritic Oxaya Formation covers the Chucal and possibly the Putani Formation and is conformably coverd by the Lupica Formation.

Along the Lauca valley widely extended (3.000 Km^2), approximately 300 m thick, slightly folded and locally, internally thrusted, lacustrine deposits with a 2,3 ± 0.7 Ma pyroclastic intercalation are exposed (Lauca Fm). On the Altiplano East of Iquique a fluvio-lacustrine equivalent of the Lauca Formation forms a 40 m high terrace on the east margin of the Coipasa Salar.

Overlying the late Pliocene deposits are the active volcanoes of the Western Cordillera and the alluvial and evaporitic salar deposits, which represent the youngest accumulations of the Altiplano.

THE WEST-VERGENT THRUST SYSTEM (WTS): DESCRIPTION AND SIGNIFICANCE.

The West-vergent Thrust System is well exposed North of 20° S along the western slope of the Chilean Altiplano, between Putre and Chusmiza villages, that is, between the Central Basin and the Altiplano (Fig. 1).

This WTS system is characterized by high angle faults that involve the metamorphic pre-Cambrian basement. There is no evidence for a basal decollement level. This thick-skinned structural style is considerably different from that developed on the east border of the Altiplano during the Cenozoic, which occured along east vergent thrust sheets (thin-skinned) (Roeder, 1988; Sempere *et al.*, 1988, 1990; Herail *et al.*, 1990; Baby *et al.*, 1992).

The faults that form the West-vergent Thrust System dip to the East and their vertical throw increases from West to East exposing the oldest units over younger units.

As a result of the uplift, widely extended syntectonic deposits were generated westward of the faults. These structures activated coalescent fluvial systems and originated "bajadas" that progradate to the West. The westernmost syntectonic deposits interfinger with the Central Basin deposits.

Structures in Moquella area

The westernnmost fault of the WTS is well exposed in the Moquella area (Fig. 2). There, fault propagation folds are developed in 16 Ma old volcanic rocks. The local vertical throw of this fault is 80 m. This system grades from South (19° 30' S) to North, from a west dipping monoclinal flexure-fold to a west-vergent asymmetric fold with two east dipping thrusts. These thrusts involve the Oxaya Formation, Tarapacá Ignimbrite and Camiña Ignimbrite (Fig. 2c). K-Ar age determinations on the Tarapacá ignimbrite, that covers the Oxaya Formation which is affected by the faults, gave ages of 16.3 and 16.2 Ma (Table 1). Rocks of the Camiña ignimbrite that cover unconformably the flexured and faulted units were dated at 8.2 Ma (Muñoz and Sepulveda, 1992). The thrust episode in this area thus occurred in the middle to late Miocene.

To the South in the quebrada Aroma, at the latitude of Iquique (21°S), sedimentary metamorphic rocks are also thrusted over volcanic units of Tertiary age with a mimimum vertical throw of 250 m.

Structures in the Oxaya Formation

At its type locality, Pampa Oxaya, the Oxaya Formation is affected by a system of faults of the WTS (Fig. 3). The structures described for the Moquella area are continued to the North by the Ausipar fault, which is the major thrust to the west of Pampa Oxaya. The Oxaya Formation is partially cut by a 50° east dipping thrust with a vertical separation of 600 m that formed a wide antiformal structure, forming part of the extensive surface of Pampa Oxaya.

Repeated activity along these faults is evidenced in the Azapa Valley, East of Arica. Here, in the east-block, that is, the back of the Ausipar thrust (Fig. 3), the Oxaya Formation overlies directly Jurassic deposits. In the west block the Oxaya Formation is underlain by a more than 100 m thick, coarse gravel deposit and overlain by another syntectonic alluvial fan deposit. This indicates the existence of at least two episodes of thrusting along this fault and the pre-Oxaya begining of the fault activity.

To the east, at the confluence of the Azapa and the Tignamar valleys syntectonic deposits are exposed. This unit is formed by aluvial fan deposits that interfinger with restricted lacustrine deposits containing rests of a late Miocene (9–8 Ma) Mammal (*Typotheriopsis* sp, Nothoungulata, Mesotherridae) (SALINAS *et al.*, 1991). These deposits wedge to the West and are thrusted by ignimbrites of the Oxaya Formation. This thrust is covered by the 4.8 Ma of Huaylas ignimbrite (Fig. 3).

North of Belén village, the fault system corresponds to imbrications in the middle Miocene volcano-detritic deposits (Lupica Formation) and thrusts of Jurassic over Miocene series and of Pre-Cambrian rocks over the Jurassic and the Miocene series. The faults thrusting the pre-Cambrian over the Jurassic rocks and those that thrust the pre-Cambrian over Tertiary rocks dip 57° to the East.

The minimum vertical throw necessary to superpose the basement rocks over the Lupica Formation is similar to the added thicknesses of the Oxaya Formation (600–800 m), the Lupica Formation (750 m) and at least 500 m thickness of the remaining Jurassic sediments, that is, 1,950.

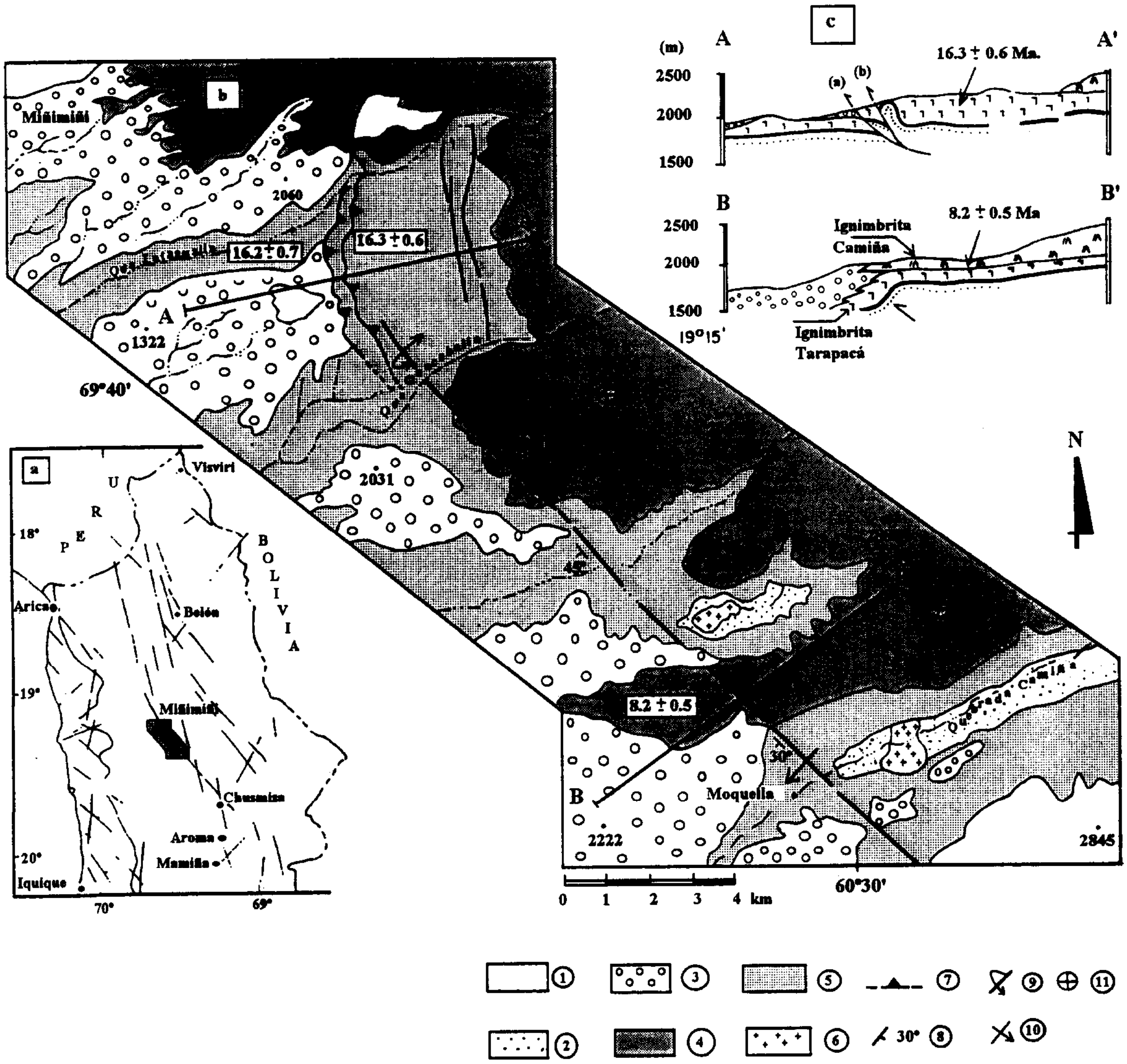

Fig. 2. The Moquella fault area (after Muñoz y Sepúlveda, 1992). **a**. Location of the Moquella fault and its position relative to the other west vergent thrust fault on the chilean versant of the Altiplano. **b**. Geological map along the east border of the Central Basin and trace of the Moquella fault (1) Cuaternary deposits, (2) Jurassic rocks, (3) Conglomerates, (4) Camiña ignimbrite, (5) Miocene volcanic sequence, (6) Diorite, (7) Contractional fault, (8) bedding, (9) Overturned bedding, (10) Monoclinal (11) Horizontal bedding. **c**. Structural profil across the Moquella fault at two diferent localities showing the northward transition from and west dipping flexure and a west vergent asymetric fold with two east dipping thrusts.

THE UPLIFT AND RELATIVE AGE SEQUENCE OF THE ALTIPLANO PLATEAU

The West-vergent Thrust System located along the western border of the Altiplano, that separates this morphostructural unit from de Central Basin and from the Precordillera on the chilean versant North of 20° South latitude, has an opposite position and vergence relative to the east-vergent thrust and fold belt of the Subandean Sierras in Bolivia (Roeder, 1988; Sempere *et al.*, 1988; Sheffels, 1990). The WTS also differs radically in style from the Sierras Subandinas thrust and fold belt.

According to Herail *et al.* (1990) the formation of the Subandean Sierras thrust and fold belt began in the late Oligocene and is still developing. The present activity is shown in the western part of the Subandean Sierras by shallow crustal seismic activity, with focal mechanisms of inverse dip-slip solution along west-dipping planes (Dorbath *et al.*, 1991). Uplift rates of the Altiplano in Bolivia, as determined by apatite and zircon fission-track cooling ages, accelerated at 15 Ma (Benjamin *et al.*, 1987). Other authors indicated that uplift was active by 10 Ma. (Allmendinger, 1986; Crough, 1983).

Gubbels *et al.* (1993) propose a two-phase model (Oligocene to 10 Ma, and after 10 Ma) of growth that links plateau uplift to the development of the fold-thrust belt, in the Eastern Cordillera and Subandean. According to Gubbels's model, in the first stage early plateau uplift ocurred in response to widespread compressional deformation of the plateau. During the second stage, upper-crustal deformation within the plateau terminated, and the Subandean thrust and fold belt developed.

Sempere *et al.* (1990) also distinguished in the Altiplano a western "belt" separated from an eastern "belt" by the "Intra-Andean Boundary Fault" (FLIA), a west

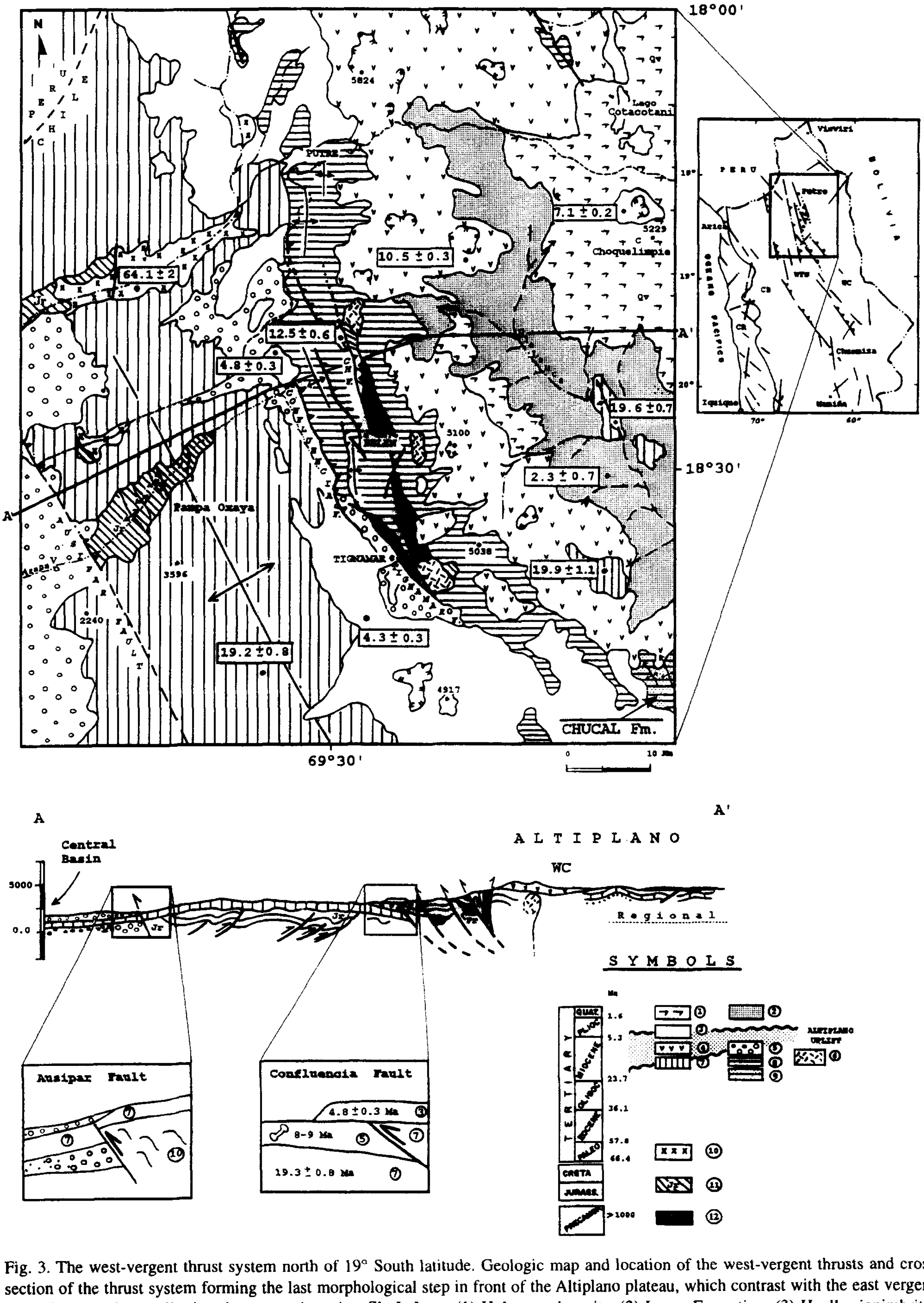

Fig. 3. The west-vergent thrust system north of 19° South latitude. Geologic map and location of the west-vergent thrusts and cross section of the thrust system forming the last morphological step in front of the Altiplano plateau, which contrast with the east vergent pre-Paleogene thrust affecting the mesozoic series. **Simbology**: (1) Holocene deposits, (2) Lauca Formation, (3) Hayllas ignimbrite, (4) Late Miocene volcanic units, (5) Syntectonic deposits, conglomerates, (6) Dacite, (7) Oxaya Formation, (8) Lupica formation, (9) Chucal formation, (10) Diorite, (11) Jurassic sequences, (12) Esquistos de Belén Formation.

vergent thrust fault, along which part of the western "belt" was underthrust beneath the eastern "belt". According to these authors the east vergent thrust and fold belt of the Subandean Sierras began with the inception of a major east vergent low angle thrust (the Main Andean Thrust- MAT) located farther East of the FLIA and progressed sequentially towards the East.

The existence of two thrust belts with opposed vergencies on both sides of the Altiplano suggests that the Bolivian-Chilean Altiplano may essentially be considerd as a compressive structure (Fig. 5).

Sequential development and timing of deformation

According to the above description of the WTS, the chronological sequence of faults indicate a propagation to the East or to the foreland, forming an overstep thrust sequence, that is, opposite to the transport direction. This fault development occurred between pre-Oxaya Formation (19 Ma) times and 4.8 Ma. The local presence of thrust faults in the late Pliocene Lauca Formation suggest that further deformation of the WTS might have occurred until the Pleistocene.

Uplift of the Chucal Formation: During the Late Oligocene-Early Miocene a lacustrine basin was formed on the west side of the Altiplano, in which the Chucal Formation was deposited (Fig. 4). Sedimentary rocks of the Chucal Formation contain evidence of their elevation at the time of deposition. Using the palinologic and paleobotanic content of this formation as a paleoclimatic tool, it is possible to indicate that the Chucal Formation was deposited under paleoecological conditions controled by a mean altitude of 1,000 ± 200 m a.s.l. (Charrier *et al.*, 1994).

Pyrolysis rock-eval, spore color index, vitrinite reflectancy indicate that the Chucal Formation underwent a maximum burial of 1,300 m, and then was uplifted to its present altitude of 4,200 m a.s.l. (Fig. 4) (Muñoz *et al.*, 1994). For simplicity the model assumes that this aumount of exhumation (1,300 m) is not isostatically compensated. According to Muñoz's model it is possible to deduce that the Chucal Formation was tectonically uplifted 4,000 ± 200 m between 15 and 4.8 Ma. This implies for this time lapse an uplift rate of 392 ± 20 m/Ma.

DISCUSSION

The western slope of the Altiplano, according to Isacks (1988), is a crustal-scale monocline, and the late Cenozoic volcanic arc or Western Cordillera, is located approximately above the tip of the asthenospheric wedge between the subducted plate and the horizontal overriding plate. This author assumes that processes in this wedge are effective in thinning the upper plate, increasing the temperature in the uppermost mantle and, thus, weakening the continental lithosphere. This author's model for the uplift of the Altiplano-Puna plateau implies that once the eastern thrust and fold belt started to develop, the underthrusted foreland continued to compress the ductile lower crust west of the thrust belt. The consequent thickening of the lower crust produced a plateaulike uplift west of the thrust belt and a west dipping monoclinal was developed to accommodate the differential uplift of the upper crust at the western limit of ductile thickening of the lower crust.

The West-vergent Thrust System along the western border of the Altiplano (WTS) prolongates the regional monoclinal flexure-fold, which, according to Isacks (1988), could be located above the tip of the asthenospheric wedge. These faults could represent the end point of the deformation that caused the crustal flexure and facilitated the uplift of the west side of the Altiplano.

With the development of thrust systems on both sides of the Altiplano the uplifted block formed a unit separated from the crust of both the foreland and the forearc, and corresponds to the configuration of an orogenic float, in the sense of Oldow *et al.* (1990).

Under these conditions the compressive stresses acting on the Andean region will compell the uplifted and possibly more buoyant crust to further override the adjacent thinner crust at both sides of the Altiplano.

Once such conditions are established the uplift process gradually developes until a major change in the subduction occurs. Slowing down of the subduction rate, interruption of the subducting plate process or changes in the orientation of the subduction are factors that may change the conditions for the uplift of the Altiplano and may lead to its collapse. An increase in the subduction rate could probably increase the uplift rate, unless climatic changes occur that increase the erosion rate in this region.

The values higher than 0,705 for Sr isotope ratios obtained for all volcanic rocks of the Central Andes younger than 15 Ma (Wörner, 1991), indicate that the crust of the Altiplano was considerably thickened and that the Altiplano certainly already existed at that time as a morphological unit.

CONCLUSIONS

It is concluded that the Altiplano is an uplifted block controlled by thrust systems at both sides (Fig. 5) that was separated in the middle to late Miocene by these thrust systems from the foreland and the forearc crust.

The east-vergent thrust and fold belt of the Eastern Cordillera and Sierras Pampeanas ("phase of tectonic build-up" of Froidevaux and Isacks, 1984) started in the late Oligocene. The west-vergent high angle thrust system on the western border of the Altiplano (WTS), that completed the build-up phase of the Altiplano, was active during the late Oligocene but, it developed more probably between 15 and 4.8 Ma. This thrust system is located above the downtip of the interplate boundary (Fig. 5).

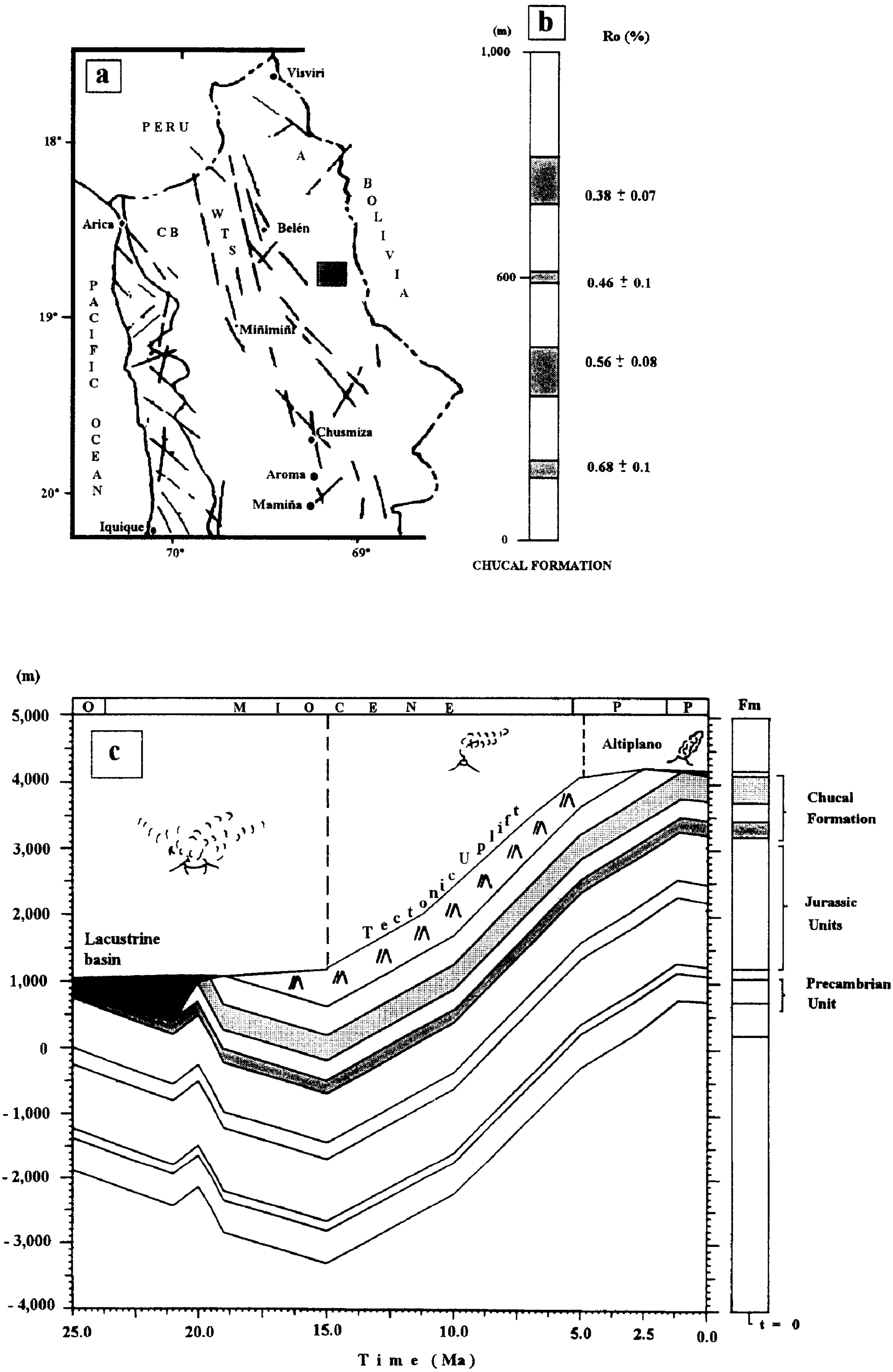

Fig. 4. The Chucal Formation in relation to the Altiplano uplift. **a.** Location of outcrops **b.** Vitrinite reflectance profile. **c.** Geohistory of the Chucal formation. After a burial history with 1,300 ± 100 m of overburden, the Chucal Formation was uplifted 4,000 ± 200 between 15 and 4.8 Ma.

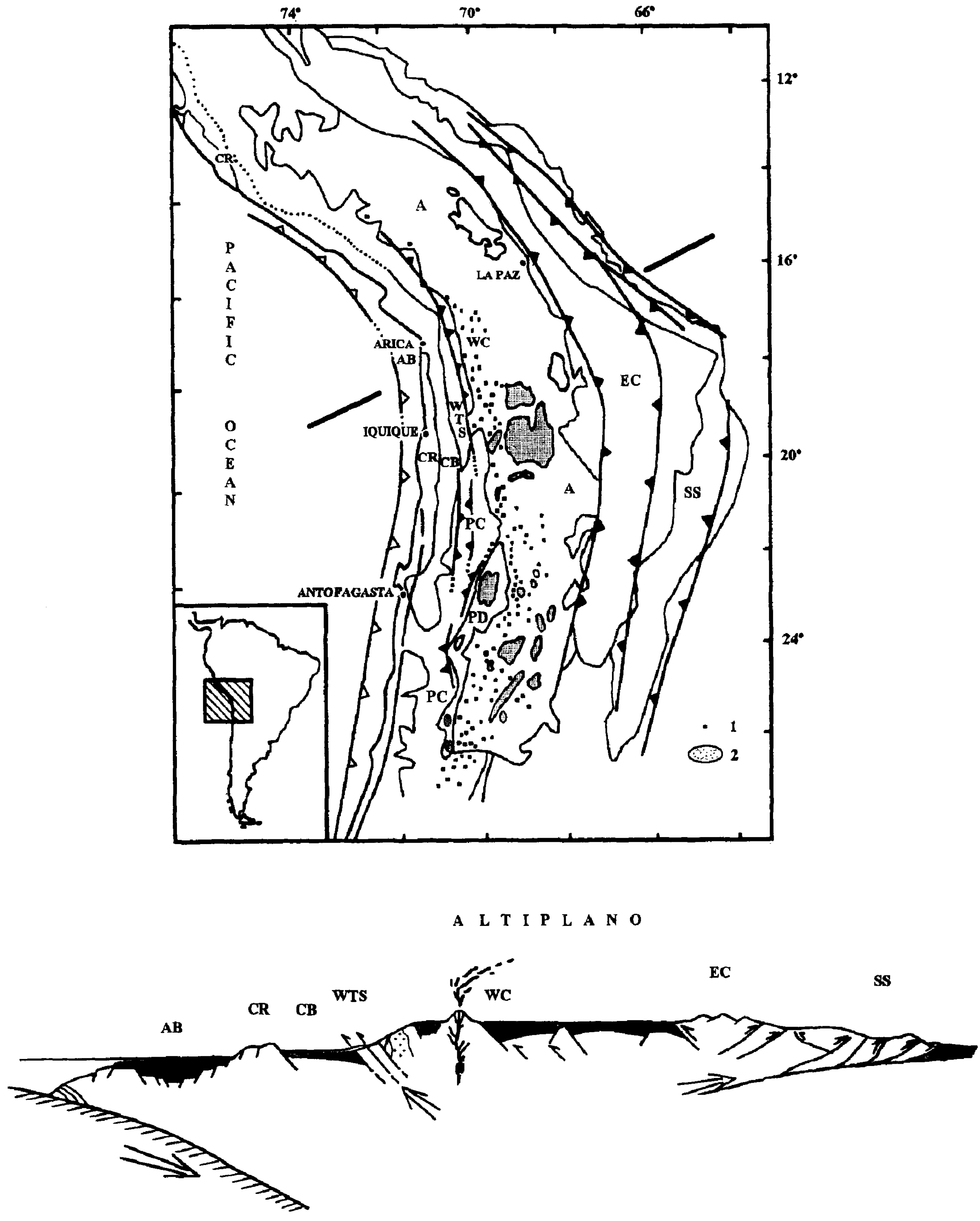

Fig. 5. Conceptual Model. Generalized section of the Central Andes of Bolivia and Chile showing the morphostructural units and the position of the Altiplano plateau between two thrust systems with divergent vergencies on each side, suggesting the compressive origin of the this uplifted block. Same symbols as in Fig. 1

The west-vergent fault system on the west side of the Altiplano and the east-vergent thrust and fold belt on the east border, indicate that this plateau is a compressive asymmetric structure formed by two thrust "belts" with opposing vergencies (Fig. 5). The westernmost system is interpreted as the rupture along a regional flexure-fold separating the Central Basin and the Altiplano.

Uplift started in the late Oligocene together with the beginning of the Subandean east vergent thrust and fold belt and was continued by both the ongoing east-vergent Subandean thrust system and the Middle to Late Miocene western west-vergent thrust system ("phase of tectonic build-up" of Froidevaux and Isacks, 1984). The development of the east-vergent thrust and fold belt from the late Oligocene to Present indicates the existence of continuous compressive stresses affecting the continental margin in this region. The uplifted Altiplano block reacted to these stresses without serious compressive deformation on its surface. Apparently these stress acted on low levels of the uplifted block causing only some extension of the upper zones that developed subsiding extensional basins. Slight local compressive deformation occurred, however, during the late Pliocene or Pleistocene, in the Lauca Formation. This compression seems to have acted only locally and cannot be considered a regional compressive phase.

The two events of thrusting on both sides of the Altiplano with different ages and opposed vergencies directed away from the Altiplano are related to different rates of uplift: a slower rate on the east side where the thrusting began earlier and a more rapid rate of 392 ± 20 m/Ma, between 15 and 4.8 Ma, on the west side.

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REFERENCES

Allmendinger, R.W., 1986. Tectonic development, southeaster border of the Puna plateau, north western Argentina Andes. Geological Society of America Bulletin, v. 97, p. 1070–1082.

Baby, P., Herail, G., Salinas, R. and Sempere, T., 1992, Geometry and kinemtic evolution of passive roof duplexes deduced from cross section balancing: Example from the foreland thrust system of the southern Bolivia Subandean Zone: Tectonics, v. 11, p. 523–536.

Baker, P. and P. Francis, 1978. Upper Cenozoic volcanism in the Central Andes, ages and volume. Earth and Planetary Science Letters, v. 41, p. 175–187.

Barazangi, M. and B.L. Isacks, 1976. Spatial distribution of earthquakes and subduction of the Nazca plate beneath South America. Geology, v. 4, p. 686–692.

Benjamin, M.T., Johnson, N.M., and Naeser, C.W., 1987, Recent rapid uplift in the Bolivian Andes: Evidence from Fission-track dating: Geology, v.15, p. 680–683.

Cahill, T.A. and Isacks, B.L., 1992, Seismicity and shape of the subducted Nazca Plate: Journal of Geophisical Research, v. 97 (12), p. 17,503–17529.

Charrier, R. and N. Muñoz, 1994. JurassicCretaceous paleogeographic evolution of the Chilean Andes at 23°24° S.L. and 34° 35° S.L.: A comparative analysis; *in*: K.-J. Reutter, E. Scheuber & P.J. Wigger (Eds.), Tectonics of the Southern Central Andes, Springer-Verlag, Berlin-Heidelberg-New York, p. 233–242.

Charrier, R., Muñoz, N. and Palma-Heldt, S., 1994, Edad y contenido paleofloristico de la Formación Chucal y condiciones paleoclimáticas para el Oligoceno Tardío-Mioceno Inferior en el Altiplano de Arica, Chile. Proceedings 7th. Congreso Geológico Chileno, v. 1, p. 434–437.

Charrier, R. and Muñoz, N., Geología Y Tectónica Del Altiplano Chileno. Proceedings 2nd. Simposio Internacional De Estudios Altiplánicos, Arica, October 1993, in press.

Crough, S.T., 1983 Apatite fission-track dating of erosion in the eastern Andes, Bolivia. Earth and Planetary Science Letter v.64, p. 395–397.

Dorbath, L., Dorbath, G., Jimenez, E. and Rivera, L., 1991. Seismicity and tectonic deformation in the Eastern Cordillera and the subAndean zone of central Peru. Journal of South American Earth Sciences, v. 4, N° 1/2, p. 13–24.

Froidevaux, C. and B.L. Isacks, 1984. The mechanical state of the lithosphere in the AltiplanoPuna segment of the Andes. Earth and Planetary Science Letters, v. 71, p. 305–314.

Galli, C., 1957. Las formaciones geológicas en el borde occidental de la Puna de Atacama, Sector de Pica, Tarapacá. Revista Minerales, Año 12, N° 56, p. 14–26, Santiago.

Galli, C., 1968. Cuadrángulo Juan de Morales, Provincia de Tarapacá. Instituto de Investigaciones Geológicas, Carta Geológica N° 18, 53 p., Santiago.

Galli, C. and R. Dingman, 1962. Cuadrángulos Pica, Alca, Matilla y Chacarilla. Instituto de Investigaciones Geológicas, Carta Geológica, v. 3, N° 2–5, 125 p., Santiago.

Ganser, A., 1973. Facts and theories on the Andes. Journal of the Geological Society of London, v. 129, p. 93–131.

Gubbels, T., Isacks, B.L. and Farrar, E., 1993, High-level surfaces, plateau uplift, and foreland development, Bolivian central Andes: Geology, v. 21, p. 695–698.

Harambour, S., 1990. Geología preCenozoica de la Cordillera de los Andes entre las quebradas Aroma y Juan de Morales, I-Región, Chile. Thesis, Dept. of Geology, Univ. de Chile, Santiago, 228 p.

Herail, G., Baby, P., Lopez, M., Oller, J., Lopez, O., Salinas, R., Sempere, T., Beccar, G. and Toledo, H., 1990. Structure and kinematic evolution of subandean thrust system of Bolivia. International Symposium on "Andean Geodynamics", May 1990, Grenoble, ORSTOM, Paris, p. 179–182.

Isacks, B.L., 1988. Uplift of the central Andean plateau and bending of the Bolivian orocline. Journal of Geophysical Research, v. 93, N° B4, p. 3211–3231.

Kono, M., Fukao, Y. and Yamamoto, A., 1989. Mountain building in the central Andes. Journal of Geophysical Research, v. 94, N° B4, p. 3891–3905.

Lahsen, A., 1982. Upper Cenozoic volcanism and tectonism in the Andes of northern Chile. Earth Science Reviews, v. 18, p. 285–302.

Mpodozis, C. and V. Ramos, 1989. The Andes of Chile and Argentina, *in* Geology of the Andes and its relation to hydrocarbon and mineral resources: Ericksen, G.E., Cañas, M.T. and Reinemund, J.A. (editors), Houston, Texas, Circum Pacific Council for Energy and Mineral Resources Earth Science Series, v. 11, p. 59–90.

Muñoz, N., Elgueta S. and Harambour, S., 1988, El sistema Jurásico en el curso superior de la quebrada de Azapa, I Región: Implicancias paleogeográficas. Proceedings 5th. Congreso Geológico Chileno, v. 1, p. A403–415.

Muñoz, N., 1991. Marco geológico y estratigrafía de un sistema fluviolacustre, Paleogeno. Altiplano de Arica, Norte de Chile. Proceedings 6th. Congreso Geológico Chileno, p. 201–204.

Muñoz, N. and P. Sepulveda, 1992. Estructuras compresivas con vergencia al Oeste en el borde oriental de la Depresión Central (19° 15' lat. Sur). Revista Geológica de Chile, v. 19, N° 2, p. 241–247, Santiago.

Muñoz, N. and Charrier, R., 1993. Jurassic-early Cretaceous facies distribution in the western Altiplano (18°-21° 30' S.L.): implication for hydrocarbon exploration. Second Symposium International de Géodynamique Andine (ISAG 93), Oxford, September 1993, Editions ORSTOM, Paris, p. 307–310.

Muñoz, N., Charrier, R. and Zentilli, M., 1994, Condiciones de enterramiento y exhumación de la Formación Chucal: Implicancias en el alzamiento del Altiplano de Parinacota. Proceedings 7th. Congreso Geológico Chileno, v. 2, p. 1404–1408.

Oldow, J.S., Bally, A.W. and Ave Lallemant, H.G, 1990. Transpression, orogenic float, and lithospheric balance. Geology, v. 18 p. 991–994.

Pacci, D., Herve, F., Munizaga, F., Kawashita, K. and Cordani, U., 1980. Acerca de la edad Rb/Sr precámbrica de rocas de la Formación Esquistos de Belén, Departamento de Parinacota, Chile. Revista Geológica de Chile, N° 11, p. 43–50, Santiago.

Roeder, D., 1988. Andeanage structure of Eastern Cordillera (Province of La Paz, Bolivia). Tectonics, v. 7, N° 1, p. 23–29.

Reutter, K.J., Giese, P., Gotze, H.J., Scheuber, E., Schwab, K., Schwarz, G. and P. Wigger, 1988. Structures and crustal development of the central Andes between 21° and 25°S; *in*: The Southern Andes, H. Bahlburg, Ch. Breitkreuz & P. Giese (Editors), SpringerVerlag, BerlinHeidelberg-New York, p. 231-261.

Salas, R., Kast, R., Montecinos, F. and Salas, R., 1966. Geología y recursos minerales del Departamento de Arica, Provincia de Tarapacá. Instituto de Investigaciones Geológicas, Boletín 21, 114 p., Santiago.

Salinas, P., Villarroel, C., Marshall, L. Sepulveda, P. and Muñoz, N., 1991. Typotheriopsos sp. (Notoungulata, Mesotheridae), Mamífero del Mioceno superior en las cercanías de Belén, Arica, norte de Chile. Proceedings 6th. Congreso Geológico Chileno, p. 314–317.

Schmitz, M., 1994, A balanced model of the southern Central Andes: Tectonics, v.13, p. 484–492.

Sempere, T., Herail, G. and J. Oller, 1988. Aspectos estructurales y sedimentarios del oroclino boliviano. Proceedings 5th. Congreso Geológico Chileno, Santiago, v. 1, p. A127–A142.

Sempere, T., Herail, G., Oller, J. and M.G. Bonhomme, 1990. Late Oligoceneearly Miocene major tectonic crisis and related basins in Bolivia. Geology, v. 18, p. 946–949.

Sheffels, B.M., 1990. Lower bound on the amount of crustal shortening in the central Bolivian Andes. Geology, v. 18, p. 812–815.

Suarez, G., Molnar, P. and B.C. Burchfield, 1983. Seismicity, fault plane solutions, depth of faulting, and active tectonics of the Andes of Perú, Ecuador and southern Colombia. Journal of Geophysical Research, v. 88, p. 10,403–10,429.

Wörner, G., 1991. Le volcanisme andin. La Recherche 228, v. 22, p. 38–45.